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MAGNETIC SUSPENSION and BALANCE SYSTEM ADVANCED STUDY - 1989 DESIGN

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ABSTRACT

The objectives of this study are to experimentally confirm several advanced design concepts on Magnetic Suspension and Balance Systems (MSBS). The advanced design concepts were identified as potential improvements by Madison Magnetics, Inc. (MMI) during 1984 and 1985 studies of an MSBS utilizing 14 external superconductive coils and a superconductive solenoid in the airplane test model suspended in a wind tunnel. The design concepts, now based on confirmed experiments, are substituted in the 1985 MSBS design to provide the new 1989 MSBS design.

Specifically, the objectives are: 1) full-scale solenoid construction and test for the F16 airplane model, 2) small-scale solenoid development toward high current density, 3) mechanical tests of new permanent magnet wings materials, and 4) a new MSBS design using these accomplishments.

The 1989 improvements over previous MMI designs are: the weight and power savings result in a 1989 inflation-adjusted cost estimate of $19.1 M compared to $21.5 M in 1985 and to $88 M in 1981. The improvements are due to: the holmium insert in the model coil; 100% of wing volume is new permanent magnet material; fiberglass-epoxy structure instead of stainless steel; and shorter saddle roll coils.

INTRODUCTION

Magnetic suspension and balance systems (MSBS) for wind tunnels have been increasingly developed and utilized during the past 25 years. The primary aerodynamic advantage of MSBS is the elimination of air flow disturbances caused by the test model mechanical support system and by the required alterations in the test model. The primary technological advantages of MSBS are that static and dynamic forces and torques on the test model can be applied and recorded (from magnet currents) without the severe sting restraints.

The potential availability of MSBS for large transonic tunnels improves steadily in line with the development of the new high temperature superconductor materials and the expanded use of low temperature superconductive magnet systems in many fields, such as: high energy physics and energy storage. Compact superconductive systems provide high magnetic fields on the test model.

The design studies by General Electric [1] in 1981 and by Madison Magnetics in 1984 [2] and 1985 [3], and a pilot model at Southampton in 1983 [4] show that practical full-size superconductive MSBS systems can be built well within the present state of the art for superconductive systems. Design improvements and cost reductions continue in this Phase II-1989 design study for a MSBS suitable for an 8' x 8' test section at Mach 0.9 with ± 0.1% control forces at 10 Hz

for an F16 model airplane.

The new conceptual MSBS designs for 8' x 8' wind tunnels in this study by Madison Magnetics Inc. (MMI) continue the trend of improvements that was started with the MMI-1984 and MMI-1985 MSBS designs. This MMI-1989 design has more flexibility in magnet choices and more control capabilities with simpler coil configurations than previously.

The objectives of this study cover experimental projects to demonstrate improved components and extensions of the MMI design studies labeled here as MMI-1989 MSBS design.

A full-scale model core solenoid is built, tested, and qualified for use in an F16 airplane model. The critical aspects of a solenoid in a tight-fitting portable cryostat container are dealt with by experimental staged improvements until a workable final system is completed. The recommendations for best design based on this experiment provide a conservative, high magnetic moment model core solenoid at 30 kA/cm^2 which will be a good candidate for the first 8' x 8' tunnel.

The use of the permanent magnet material Nd-Fe-B (Neomax trade name) for wings of an F16 model is solidified by bending strength measurements which show that Neomax is strong enough to use without stainless steel skin support. The general replacement of magnetized soft iron wings by high performance rare earth permanent magnet material is an enormous advance for MSBS model roll characteristics. External superconductive

roll coils can thereby be significantly smaller, less powerful, and less expensive.

An extended MSBS design is undertaken to essentially solidify the 1985 design with the actual experimental achievements replacing previous conceptual designs. The solenoid parameters are about as predicted, except now the magnetic moment is known and proven. Not all design and construction choices were best; in particular the design was too tight as a result of trying for too high a magnetic moment. But at least now it is known what is critical and what should be achieved. A clear example of one item illustrates the more general conclusions to this work: in a prescribed 75 cm long envelope MMI built and tested a solenoid with active windings 70 cm long, which leaves only 2.5 cm on each end for support and thermal transition from 4.2 K to 300 K. Based on this construction experiment we recommend 5 cm on each end to get better helium hold time.

The MMI-1989 redesign has an improvement of 30% reduction in ampere-meters and 50% reduction in energy stored in the 14 suspension coils over the 1985 design. These improvements are mainly due to the removal of skin support in model wings and optimizing the locations of the 14 suspension coils.

MODEL SOLENOID AND CRYOSTAT

Model Solenoid

The goal of constructing and testing high current density model solenoid with holmium core is to demonstrate that a high

pole strength and high magnetic moment practical solenoid can be built to commercial specifications, and become certified as available for use.

Table 1 lists the model solenoid (shown in Figure 1) parameters. The parameters along with the holmium mandrel achieves the 4.45 X 10^4 Am magnetic pole strength as listed in Table 2.

Table 1
Magnet Parameters

Magnet A	
(1) Winding inner diameter	3.263 in. (8.288 cm)
(2) Winding outer diameter	4.459 in. (11.326 cm)
(3) Winding length	12.904 in. (32.776 cm)
(4) Number of turns	24,849
Magnet B	
(1) Winding inner diameter	3.263 in. (8.288 cm)
(2) Winding outer diameter	4.459 in. (11.326 cm)
(3) Winding length	12.997 in. (33.012 cm)
(4) Number of turns	24,854
The parameters for the assembled system are:	
Total turns	49,703
Total ampere-turns needed	3,326,606
Current required	66.93 A
Field at the windings (no holmium)	6.16 T
Inductance (no holmium)	29 H
Persistent switch heater current	0.039 A
Magnet charge rate	4 A/min.

Table 2

Initial Model Coil Specifications

	ID (cm)	OD (cm)	LENGTH (cm)	WEIGHT (kg)	MAGNETIC POLE STRENGTH (Am)
Winding	8.26	11.5	70	26.8	3.75×10^4
Mandrel	6.14	8.26	70	14.5	0.70×10^4
Total				41.3	4.45×10^4

The solenoid manufacture is conducted according to ordinary commercial standards to demonstrate that such solenoids could be routinely available. The manufacturer, American Magnetics (AMI) was free to select the conductor, lead system, protection system and winding design details. The conductor is a standard 1.35:1 Cu:NbTi ratio. AMI wound the coil in two half-coils with the current contacts being made in the center. Breaking the coil in the center also facilitates the assembly of the persistent switch and diodes which are located inside the magnet bore for lack of space to put them elsewhere.

In constructing the magnet, the holmium cylinders are machined down to a smaller OD than the stainless steel mandrel ID to prevent cooldown over-stressing the windings.

During magnet tests, the two magnet half core tested individually at 4.2 K both achieving 72 and 73.3 A. The magnet system is then assembled and tested several times as a unit.

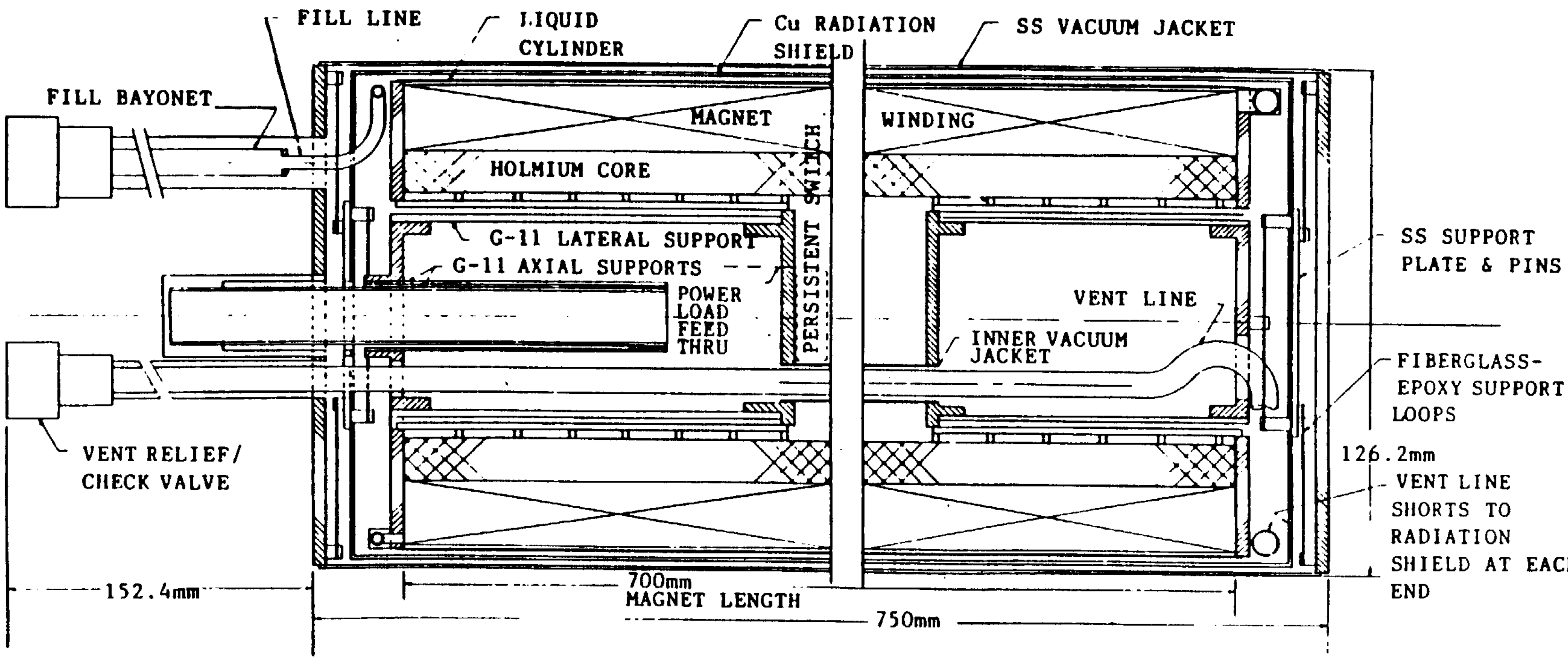


Figure 1. Core Magnet Cryostat.

The first two tests became shakedown tests to fix leaks that initially prevented achieving 5 psi (gauge), and to change the persistent switch for locking at 5 psi.

July 28, 1988	The third test went to 70 A without transition, and was pressurized to 5 psi*. The switch was locked in and the magnet was left in the persistent mode for 20 minutes. While maintaining the pressure of 5 psi, the magnet was discharged and charged again to 70 A. The switch was locked in again, and the magnet remained in the charged condition for 1 hour without problem. After discharge, the pressure was released, and the system warmed up.
July 29, 1988	In the final test holmium cylinders were installed in both halves of the magnet. The magnet then was charged to the desired current of 66.9 A. The switch was locked in and the system pressurized to 5 psi, and discharged and charged 5 psi pressure. The switch operated without trouble. Several cycles to 66.9 A followed without quenches.

Such performance is satisfactory and meets all requirements for commercial acceptance. In operation a build-up of pressure to 5 psi is planned.

* 5 psi is the pressure for off-gassing after final assembly and is at 4.55 K.

Model Cryostat

The designed and constructed cryostat is shown in Figure 1. Considerations for thin materials, close alignment, and tight spacing dominate the manufacturing process. A careful design and a high level of welding craftsmanship is required to deal with the thin materials and tight mechanical specifications. The close alignment requirements are intentionally severe in order to achieve a maximum magnetic moment.

The most difficult assembly operations are due to the tight spacing. However, these fabrication challenges are acceptable and do not require any redesign. The redesign of the next cryostat, based on the results of all experiments, would include the following key items.

1. The space between each end of the winding mandrel and the outer container would be 5 cm (increased from 2.5 cm).
2. The G-11 CR cantilevered re-entry support cylinders on each end would be much stiffer to limit deflection.
3. The coil would be wound with 20 to 30 A wire to reduce lead losses.
4. The helium annular region around the solenoid would be 0.34 cm.
5. Such redesign would simplify construction and repair and achieve the helium hold time of 5 hours.

System Test of Solenoid and Cryostat

Successful electrical and cryogenic tests used 200 liters of liquid helium. Several preliminary current ramps had premature quenches in the 15-25 A range. After increasing the helium flow-through, the quenches take place in the 60-67 A range. Each run is a slow current ramp-up at .05 to 0.1 A/sec and requires about 30 minutes for the sequence of warm-up (quench) plus cooldown plus current ramp. The training sequence was 63 A, 64 A, 66.9 A, 67 A, and 67 A. During all runs, the helium flow rate and current charging rates are varied. The solenoid meets specifications of 66.9 A.

The persistent current switching is easy to operate. The AMI power supply has a second built-in small power supply to heat the persistent switch across the solenoid. By turning off the heater power, the switch becomes superconducting and traps the existing current in the solenoid and, at the same time, is a short circuit on the leads from the solenoid power supply. A series of switching on-off steps and a long persistent hold at 60 A demonstrates that the system operates disconnected from the power supply. Thus, the system meets all specifications.

The cryostat and solenoid manufacture and tests are successfully completed and qualified per specifications.

WING MAGNETIC MATERIAL

An MSBS magnet system must be capable of rolling the airplane model around its longitudinal axis. Roll is achieved

by exerting a magnetic torque on the magnetic model wing. In this design the wings are fabricated from permanent magnet material, $Nd_2Fe_{14}B$. The mechanical bending strength of the wing at ambient and liquid nitrogen temperatures determines if the wing is self-supporting or must be supported by an extra stainless steel skin as shown in Fig. 2. A steel skin is undesirable because it occupies space that could have been magnetic material. The purpose of this test is to measure the ultimate bending strength of the wing magnet material.

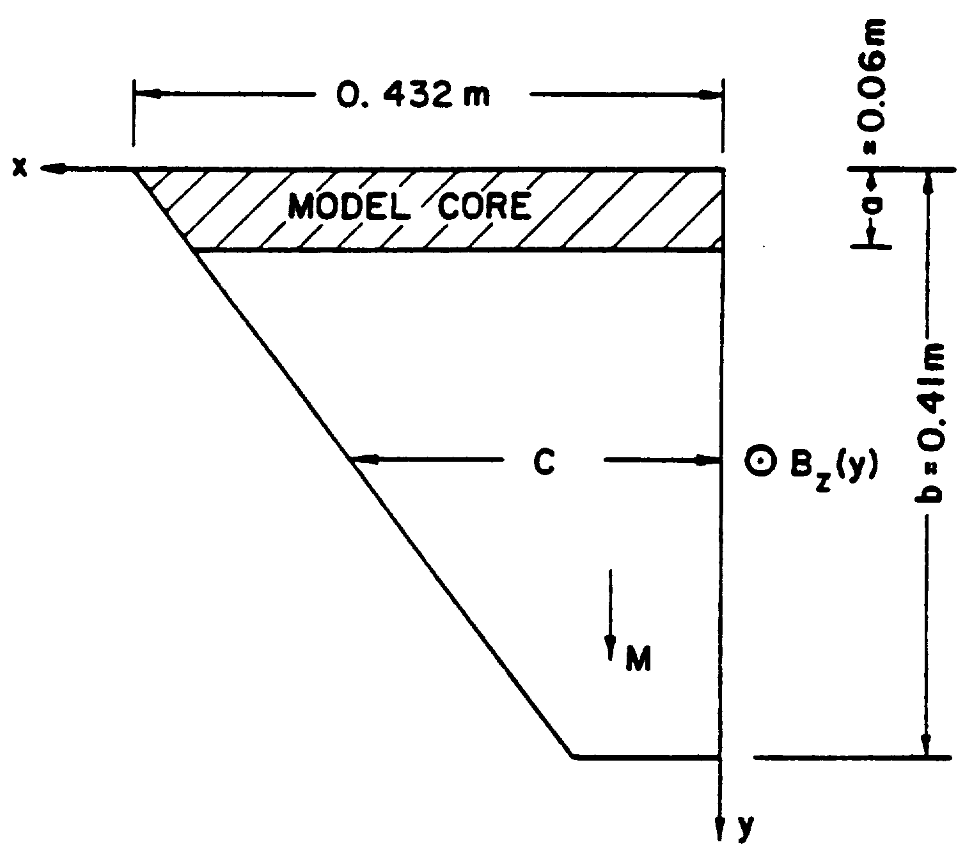


Figure 2. F16 Fighter Wing.

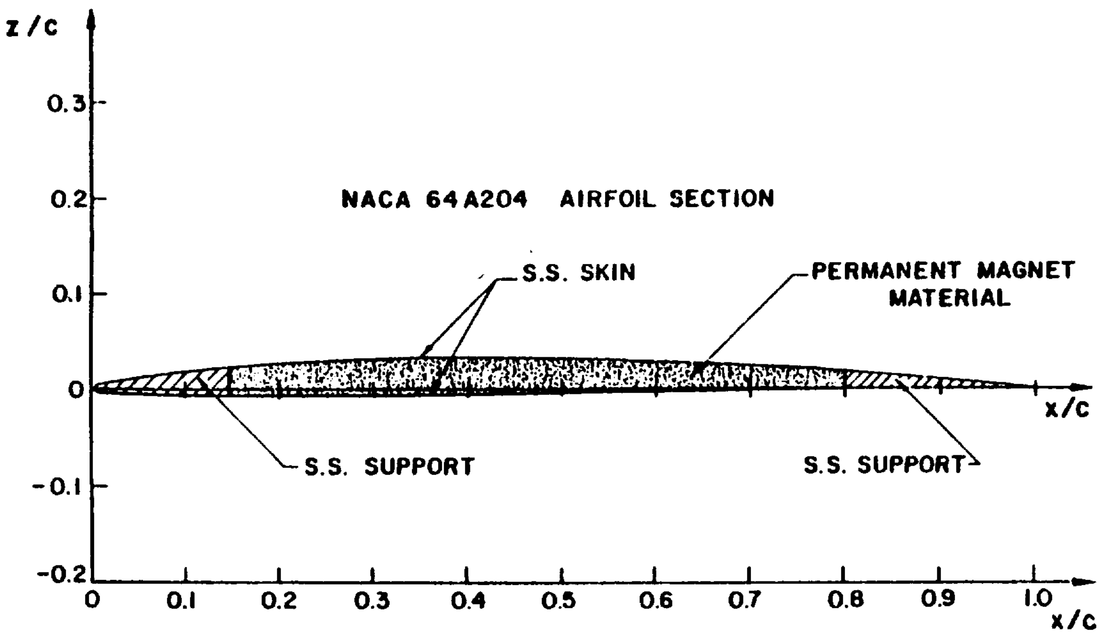


Figure 2a. Wing Cross-Sectional Area at any Chord C Showing Stainless Steel Support, Skin, and Permanent Magnet Material

Experiment Design

A three-point load test fixture is used with a hydraulic testing machine. The load is measured with a calibrated load cell. A continuous flow of liquid nitrogen keeps the sample immersed in LN_2 during the low temperature test.

For the low temperature test, the sample in the test fixture is held in place with adhesive tape inside the empty nitrogen container. The crosshead is lowered gradually until

the loading cylinder touches the specimen and loads the specimen to about 15-20 lb. At this point LN_2 is transferred to the dewar. Once the liquid covers the specimen completely, load is gradually increased until failure. The same procedure is followed at ambient temperature without the nitrogen.

Neomax-35 Samples

$Nd_2Fe_{14}B$ material is available in various shapes and dimensions from Sumitomo Special Metals Co. under the commercial name Neomax. It is available in both magnetized and non-magnetized states. The samples are 0.375" diam x 1.375" long rods with aspect ratio (L/D) = 3.93. Although this is less than the recommended aspect ratio for flexure testing, it was the closest commercial size available. At this aspect ratio the shear deformation is important. However, because there is no need to measure the material modulus, the shear effect is neglected. Physical and mechanical properties of Neomax are listed in Table 3. Magnetic properties of Neomax as tested by the vendor are shown in Fig. 3.

Table 3

Physical and Mechanical Properties of the Neomax Wing Material

Density (g/cm^3)	7.4
Electrical resistivity ($\mu\Omega cm$)	144
Vickers hardness (H_v)	600
Flexural strength (MPa)	250
Coefficient of thermal expansion Parallel ($10^{-6}/K$) Normal ($10^{-6}/K$)	 5.8 -1.3
Specific heat (cal/kgK)	120
Thermal conductivity (cal/mK)	7700
Young's modulus (GPa)	160
Rigidity (GPa)	64
Poisson's ratio (υ)	0.24

Test

Three specimens are tested to failure in liquid nitrogen and one is tested to failure at ambient temperature and compiled in Table 4. The ambient temperature bending strength is in good agreement with the typical material strength quoted by the manufacturer. The average ultimate strength at LN_2 is 50% higher than the room temperature strength. However, there is no difference in the typical brittle failure mode at the two temperatures. Tension cracks are initiated in the most stressed fibers and then propagate perpendicular to the sample axis.

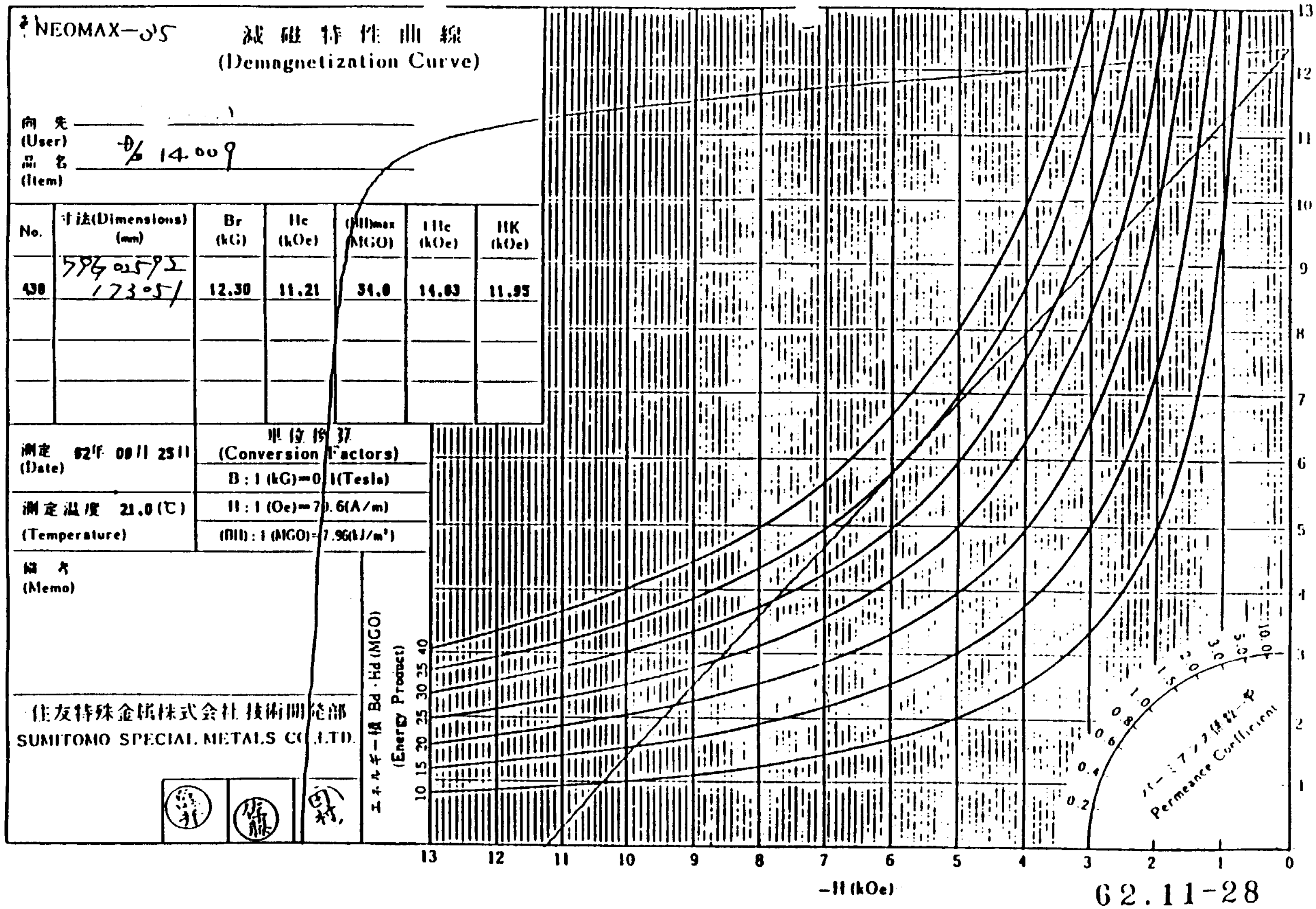


Figure 3. Magnetic Properties of the Tested NEOMAX-35 (Nd Fe B Material)

Table 4

Ultimate Bending Strength of NEOMAX-35 at 300 and 77K

Sample #1 at 77K	412 MPa
Sample #2 at 77K	417 MPa
Sample #3 at 77K	368 MPa
Average strength at 77K	397 MPa
Sample #4 at 300K	264 MPa

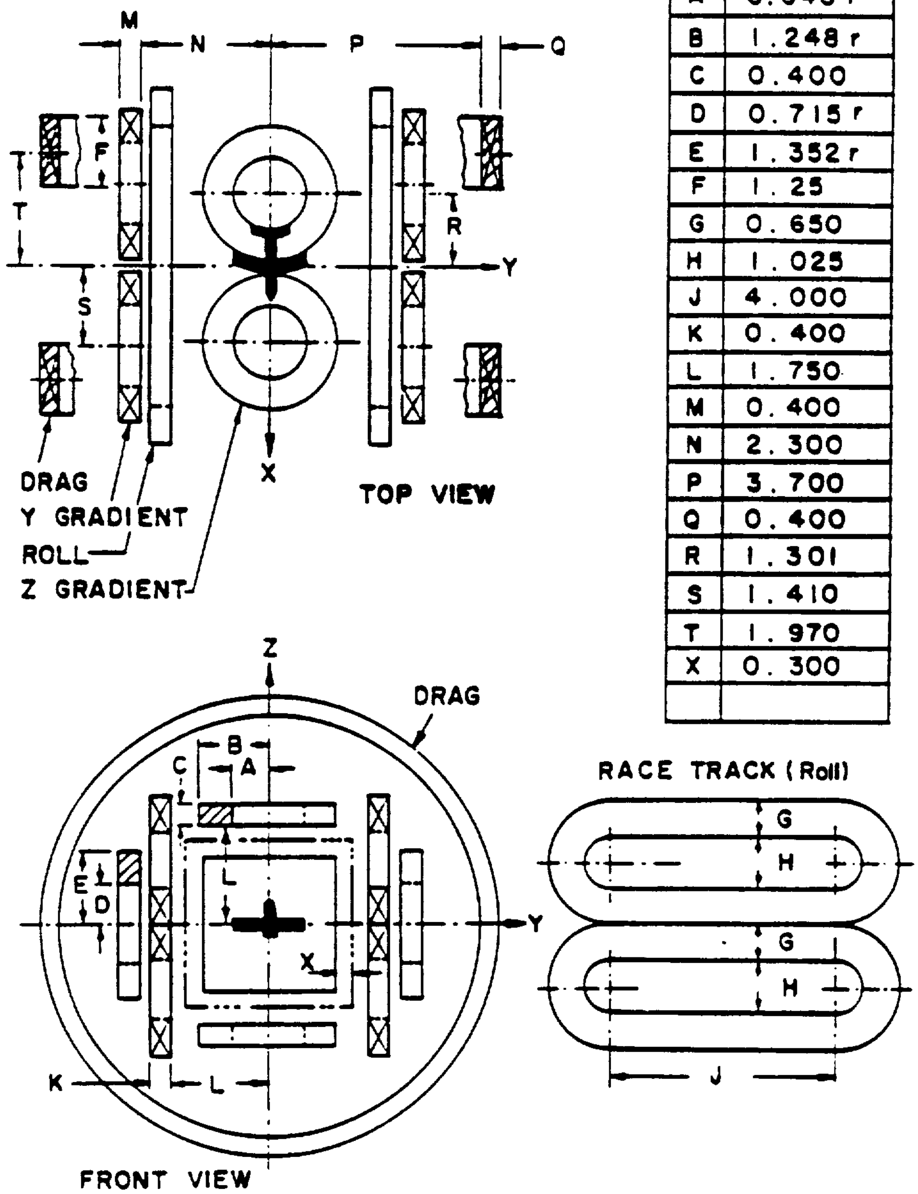
The wing material is strong enough to be self-supporting. The Neomax can fully occupy the wing volume. Therefore, the wing can provide 15% higher volume magnetization than used in the MMI-1985 design of the wind tunnel MSBS.

MSBS DESIGN

Background

The 1984 [2] and 1985 [3] MSBS designs by MMI include design improvements which reduce the costs to less than 25% of the earliest estimates [1]. The major improvements for the 1984 system, sketched in Fig. 4 are:

- A 70 cm long potted persistent superconducting solenoidal coil, 11.5 cm O.D., and 6.1 tesla is the model core. A superconducting coil produces higher magnetic moments and pole strengths than a magnetized iron core or a permanent magnet core.
- The model wings contain permanent magnets that occupy 85% of the wing volume; 15% of the wing



DIMENSIONS (m)	
A	0.643 r
B	1.248 r
C	0.400
D	0.715 r
E	1.352 r
F	1.25
G	0.650
H	1.025
J	4.000
K	0.400
L	1.750
M	0.400
N	2.300
P	3.700
Q	0.400
R	1.301
S	1.410
T	1.970
X	0.300

Figure 4. 1984 MSBS Magnet System.

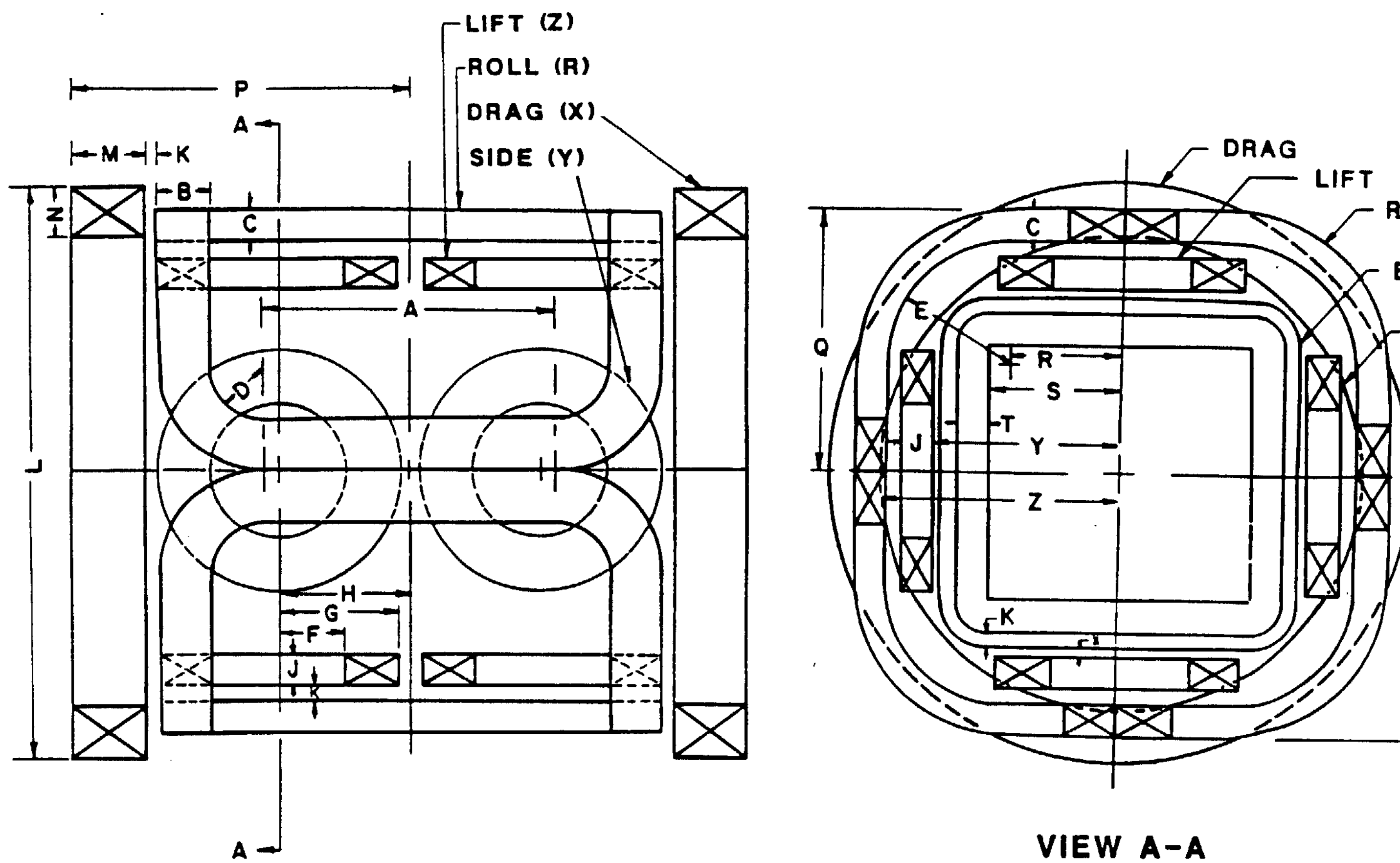
volume is high strength stainless steel.

- Z and Y gradient coils in Fig. 4 are symmetric arrays of four bipolar solenoid to control and manipulate the model. The superconductor composite-conductor for all coils is an 11-kA low-loss cryostable conductor.
- The drag coils to counterbalance wind drag forces are large diameter solenoids.
- The roll R coils are four race-track coils optimized for minimum ampere-meters.

The 1985 MSBS design (Fig. 5) added four major improvements:

1. A holmium coil mandrel in the suspended model to increase the core pole tip magnetic moment by 18.7% from 3.75 x 10^4 Am to 4.45 x 10^4 Am.
2. A new permanent magnet material $Nd_{15}Fe_{77}B_8$ in the suspended model wings which reduces the external roll magnet size by about 25%.
3. New roll and drag coils shown in Fig. 5 for a more economical and compact design.
4. Fiberglass-epoxy slabs as the principal structure to reduce ac losses.

These four improvements reduced the ampere-meters and energy stored in all 14 external magnets as shown in Table 5.



DIMENSIONS (m)	
A	2.800
B	0.500
C	0.300
D	0.500
E	1.200
F	0.644
G	1.153
H	1.250
J	0.300
K	0.152
L	5.514
M	0.700
N	0.500
P	3.252
Q	2.505
R	1.005
S	1.219
T	0.305
X	0.076
Y	1.753
Z	2.205

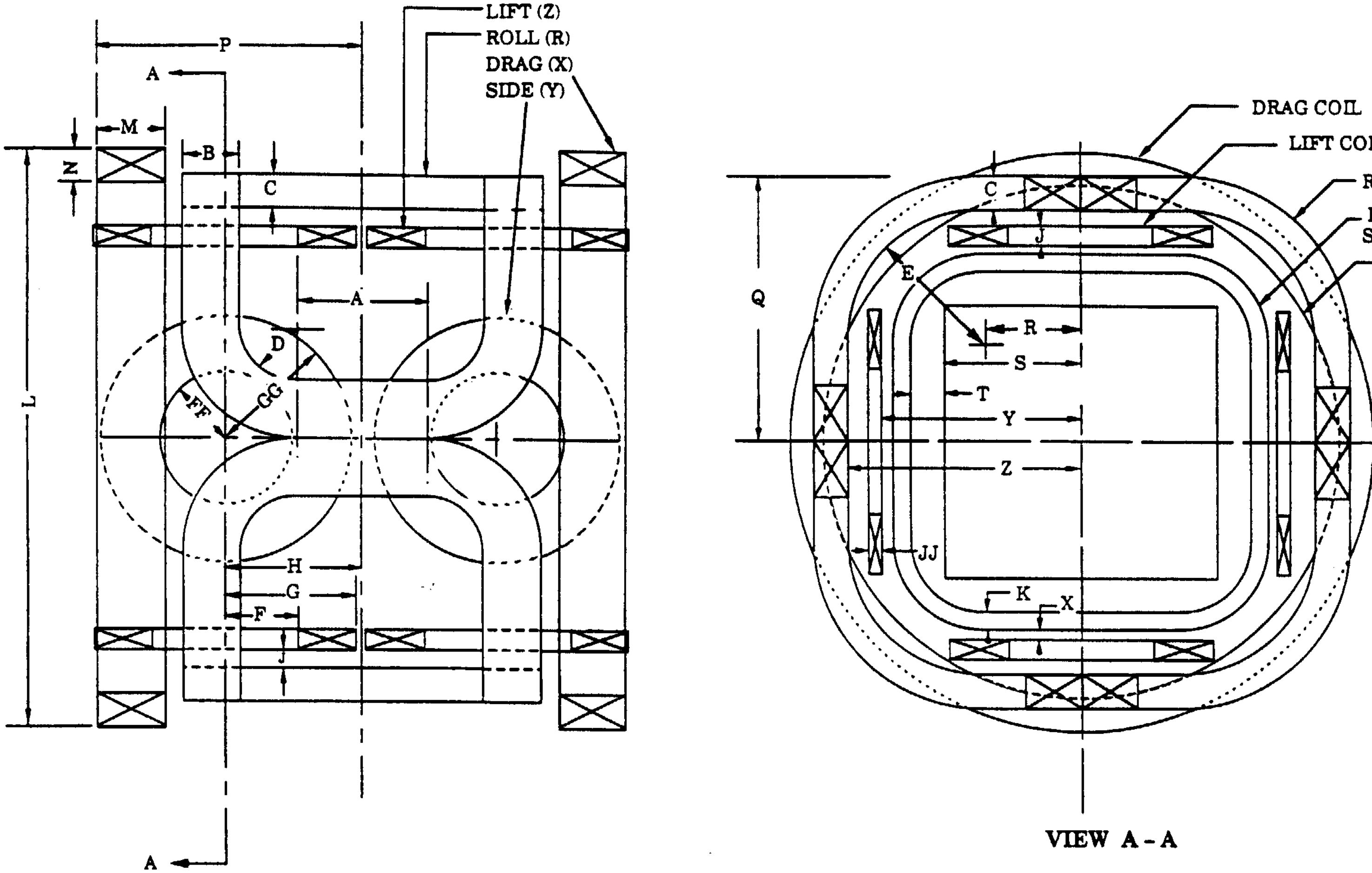
Figure 5. 1985 MSBS Magnet System

1989 MSBS DESIGN

In 1989 further improvements are based on tests of a full-size superconductive solenoid model coil; tests of wing materials; and with design improvements. These improvements yield 30% ampere-meter savings over the 1985 MSBS design. The 1989 MSBS design changes are:

1. Elimination of stainless steel support in the wings, which occupied 15% of the wing volume. Mechanical tests of wing materials show that the Neomax is strong enough to be self supporting to withstand maximum magnetic and lift forces.
2. The tested model core solenoid achieves 92% of the projected magnetic moment assumed in 1985.
3. Smaller roll R coils result from the 100% volume of magnetic material in the wing and allow a more optimum rearrangement (see Fig. 6).

The 1989 improvements in ampere-meters and energy stored are seen in Table 5.



DIMENSIONS(M)	
A	1.200
B	0.500
C	0.300
D	0.500
E	1.200
F	0.650
FF	0.600
G	1.175
GG	1.100
H	1.200
J	0.180
JJ	0.120
K	0.152
L	5.200
M	0.600
N	0.300
P	2.352
Q	2.385
R	1.005
S	1.219
T	0.305
X	0.076
Y	1.753
Z	2.025

Figure 6. 1989 MSBS Magnet System

Table 5

Madison Magnetics MSBS 1984, 1985 and 1989 Designs

COILS	X	Y	Z	R	TOTAL	%
1984 Design						
Ampere-meters (MAm)	362	100*	86	207	755	100
Energy Stored (MJ)	656	60	50	140	906	100
1985 Design						
Ampere-meters (MAm)	172	71**	71	154	468	62
Energy Stored (MJ)	216	38	38	116	408	45
1989 Design						
Ampere-meters (MAm)	106	53	74	108	341	45
Energy Stored (MJ)	93	25	44	58	220	25

* The Y coils in the 1984 design are recalculated for this table to correct an earlier error.

** Actual ampere-meters needed for Y coils are 63 MAm. For simplicity of design and to have a complete symmetry, the Y coils are sized the same as the Z coils.

The ampere-meters of conductor in the 1989 design decrease to 45% and the stored energy decreases to 25%, with comparable system savings as shown in Table 5.

CONCLUSION

The study has experimentally confirmed several advanced design concepts on magnetic suspension and balance systems. The 1989 MSBS redesign is based on the results of these experiments. Savings up to 30% in supporting magnet ampere meters and 50% in energy stored over the 1985 design are achieved.

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